

What We Know and What we Don't Know About the Universe *

Marcelo Gleiser[†]

Department of Physics and Astronomy Dartmouth College Hanover, NH 03755, USA

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I present a non-technical and necessarily biased and incomplete overview of our present understanding of the physical universe and its constituents, emphasizing what we have learned from the explosive growth in cosmological and astrophysical data acquisition and some of the key open questions that remain. The topics are organized under the labels *space*, *time*, and *matter*. Most bibliographical references are for the non-expert.

I. INTRODUCTION

It is true that the words “cosmology” and “revolution” have appeared together in many reviews and lectures in recent years. Even though to a cynic it may seem that cosmologists produce a lot of hot air, I claim that there is indeed reason for this excitement. Until the mid-sixties, cosmology was regarded with much suspicion by many scientists, who thought it closer to metaphysics than to physics. The reason for the skepticism was an appalling lack of observational data, or at least consistent observational data. For example, since the time of Hubble, the universe’s age has varied from 2 billion years (mcu below the known Earth’s age even in 1929) to over 20 billion. Its geometry has been bent and closed like the surface of a sphere, flat as a tabletop, or bent and open like the surface of a saddle. (Of course, generalized to 3 spatial dimensions.) Its material composition has also been a mystery: which chemical elements are made in stars and which during the first moments after the “bang”? What of other, exotic kinds of matter? And what about the cosmological constant? Is it there or not? And if it is, what is it? [1] Questions related to the shape, age, and material composition of the cosmos have been at the forefront of cosmology since Einstein’s pioneering use of his theory of relativity to the study of the universe as a whole.

Controversy is a good thing for science only when there are ways of resolving it. This is why these are exciting times for cosmology. We have convincing answers to many of the questions above, and are close to answering some more. Of course, this does not mean that cosmology is approaching its end. Quite the contrary, as with any mature area of science, new technologies and observational tools will continue to provide both answers and new questions and surprises.

II. SPACE

In astronomy and cosmology the yardstick is the light-year (ly), the distance covered by light in 1 year, equal to 9.46×10^{12} km. That’s 63,200 times the Earth-Sun distance, also known as astronomical unit (A.U.). Pluto is at about 40 A.U. from the Sun. Oort’s cloud, the nursery of long-period comets at the outskirts of the solar system, is at roughly 100,000 A.U., about 1.58 ly from the Sun. The nearest star, Proxima Centauri, is at 4.29 ly from the Sun. So, when people say that interstellar space is mostly empty you better believe it. At least of “visible” stuff. It turns out, paraphrasing the fox in Saint Exupéry’s *The Little Prince*, “what is essential [to the universe] is invisible to the eye.” Invisible but very real, as will be seen below.

Once we start thinking about other stars, it is inevitable to ask if there are other planets as well. The thought that our solar system is unique in some way brings nightmares to most (but not all) post-copernican scientists. Although the curiosity about extrasolar planets existed for as long as modern astronomy (and before [2]), the hunt started in earnest in the mid-1990s when minute variations of stellar light frequency could be detected due to improved observational technologies and computer data analysis software. At the time of writing (January 2004), 104 planetary systems with 119 planets have been detected [See www.obspm.fr/planets]. The curious lack of multiple planetary systems is most probably due to the limitations of the observational methods; one should not consider this as any indication of our uniqueness. NASA (Terrestrial Planet Finder Mission) and the European Space Agency (Darwin Mission) are formulating competing (possibly future collaborations) missions with a projected capability of not only

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[†]Electronic address: gleiser@dartmouth.edu

imaging Earth-size planets in the infrared but also of studying the chemical composition of their atmospheres. The goal is to explore the possibility that these planets may harbor life. We may know the answer within a decade or two. Or sooner, if programs like SETI are successful, or if we receive a visitor or message. Improbable but not impossible.

Jumping farther out, the Milky Way – our home galaxy – is a spiral containing about 300 billion stars and diameter of 100,000 ly or 30 kpc, where kpc stands for 10^3 parsecs. (1 pc equals 3.3 ly.) Strong evidence indicates that a giant black hole with a mass of about 3 million suns is at the dead center of the Milky Way, at Sagittarius A. Possibly most other galaxies also host giant black holes at their centers, given the huge outpour of radiation many produce at varying wavelengths. If you think 3 million solar masses is large think again; observations indicate that the huge galaxy M87 in the Virgo Cluster host a black hole with 3 *billion* solar masses.

Which brings me to clusters of galaxies and to the large-scale structure of the universe. The Andromeda galaxy, our nearest neighbor, is at about 2.5 Mly (million light-years) from the Milky Way. As we consider distances of millions of light-years, galaxies become the units by which we visualize the cosmos. When the Hubble Space Telescope or other large terrestrial telescopes image deep space, the light they collect as point or small sources is coming from huge galaxies millions and even billions of light-years away. What we see as stars when we look at the night sky, large-scale astronomers see as galaxies, each with millions or billions of stars. And what they see is that galaxies may coexist in groups or clusters due to their mutual gravitational attraction, like islands in an archipelago. Furthermore, galaxies and cluster of galaxies are not randomly distributed across space; they tend to collect in curved sheet-like surfaces, reminiscent of the shapes we see in bubble baths. Only at distances of 100 million Mpc or more these “bubbly” structures seem to disappear, with the universe becoming smoother.

One of the successes of modern cosmology was to shed partial light on the origin of such complex large-scale structures. The answer involves of course gravity as the conductor, and three players: ordinary, or baryonic, matter, the stuff made of protons as we are; a different kind of matter known as dark matter [3], which we know exists from its gravitational pull on ordinary matter (there are some dissenters, though); and small energy inhomogeneities, the seeds that cause matter (first dark and then baryonic) to start condensing. You may think of these energy inhomogeneities as lumps in an otherwise smooth cookie dough, regions where the local density of energy (recall that matter and energy are treated equally in relativity) varies from the average. So, we need three players. Computer simulations using them at the right proportions (more about that later) reproduce quite well astronomical observations. But what is this dark matter stuff, and what was the mechanism that generated the seeds that triggered structure and galaxy formation? We will leave dark matter for later. It is believed that the inhomogeneities were originated during the earliest moments of cosmic existence, in a process called inflation[4]. During inflation, the universe expanded extremely fast. Even small fluctuations in its quite smooth energy were amplified enormously. Those are the culprits for large-scale structure, some 100,000 years after inflation ended. Although there is no compelling model for inflation based on what we know of particles physics, the core idea and its predictions seem to be in excellent agreement with observations. If nothing else, the final answer will contain some of its elements.

What of the shape of the whole cosmos? When Einstein wrote his paper on cosmology, he assumed the universe was static and with the closed geometry of a 3-sphere. At the time, there was no compelling reason to suppose otherwise, and spheres, since the time of the Pythagoreans, have had an alluring effect on the minds of philosophers and scientists alike [5]. A spherical universe is closed yet has no boundary, and all its points are equivalent. (Imagine the surface of a perfect ball.) The question remained open until the advent of inflation in the early-1980s. For when one talks of an expanding universe, one is referring to an expanding geometry, as if the surface of a ball were inflating like a party balloon. (But no one is blowing on it from the outside!) All points rush away from each other, and distances increase at tremendous rates. Imagine then the balloon inflating, and focus your attention on a patch on its surface. As it inflates, the patch becomes flatter. An enormous amount of inflation leads to a practically flat patch. This patch, according to inflationary cosmology, is where we live. Thus, inflation predicts a flat cosmos. This prediction has been spectacularly confirmed by observations of the cosmic microwave background (CMB), the fossil radiation from the time cosmic structure started to form [6].

But our cosmos may be flat only locally. We can’t say much about other folds of the cosmos, far removed from us. In fact, we will never be able to know about those remote cosmic regions, as no signal can be sent or arrive from there in able time: light is only so fast, and our cosmic patch has been around for about 13 billion years. We cannot see beyond the flat island of 13 ly radius we call our universe. Some models of inflation even predict that the universe is really a “multiverse,” a bubbling soup of cosmoids forever bursting in and out of existence [7]. We will have to wait a bit on this one.

III. TIME

The big bang model is our current best description of cosmic history. It states that the universe had a very hot and dense infancy, and that it has been expanding ever since. There is now excellent concordance between different

methods that estimate the age of the universe. Here are a few: Measurements of the Hubble constant all the way to galaxies at 500 Mpc give $H_0 = 72$ km/sec/Mpc in a universe with 1/3 matter and 2/3 dark energy (more about this soon). This results in an age of $t_0 = 13 \times 10^9$ years with an uncertainty of 1.5×10^9 year [8]; measurements of the CMB, independent of H_0 , give $t_0 = 13.7 \pm 0.2 \times 10^9$ years [9, 10]; Finally, the ages of the oldest stars in globular clusters are estimated to be about 12.5×10^9 years [11]. A consistent age is $t_0 = 13.5 \pm 1.0 \times 10^9$ years.

Within the big bang framework, the evolving cosmic history is a history of increasing complexification: at the earliest times, matter was broken down to its smallest components. To understand cosmic history is equivalent to recreate how the structures that make up the material universe emerged. Complexification happened in stages, controlled mostly by the cosmic temperature. At a given temperature, only certain particles or their bound states (atomic nuclei, atoms, perhaps solitons) are in thermal equilibrium with the ambient radiation. One may picture this as a love triangle, where photons and possibly other light particles such as neutrinos (the radiation) interact with matter particles which are trying to bind. If these interactions proceed fast enough, the particles (or their bound states) are in equilibrium; otherwise, they are left behind as fossils of this era. Since different interactions have different associated energy (temperature) scales, the cosmic history evolves in stages, depending when a certain interaction goes out of equilibrium, from the most to the least energetic. Thus, the early cosmic history went through at least three stages: a particle era, a nuclear era, and an atomic era. The boundary between the particle and nuclear eras is at about 10^{-5} sec, when quarks and gluons combined to make the baryons, particles that interact by the strong nuclear force such as protons, neutrons, and mesons [12]. Since protons have lifetimes of at least 10^{31} years, we can say that they are fossils from this era. Once protons and neutrons were around, they could start to bind into the lightest nuclei, H_2 , H_3 , He_4 , He_3 , and Li_7 . This happened when the universe was about 1 minute old. One of the great triumphs of the big bang model is predicting successfully the abundances of these nuclei. In particular, He_4 account for about 23% of the baryonic matter in the cosmos, and hydrogen to about 75%.

The next step in the cosmic history is the formation of hydrogen atoms, at about 380,000 years. This is when protons bind with electrons and photons are free to roam across space, responding here and there to variations in the average energy density by having cold and hot spots. Measuring the properties of these photons, known as the CMB, is equivalent to taking a snapshot of the universe at that early time [13, 14]. From then on, the universe became transparent to radiation. This means that it is impossible to try to study the cosmos before this time by direct measurements of electromagnetic radiation of any wavelength; to probe the early universe we need to hunt for fossils. Dozens of terrestrial missions and the satellites COBE and WMAP (and soon PLANCK) have produced high precision measurements of the CMB, re-energizing modern cosmology and confirming yet again the predictions of the big bang model. Measurements of the CMB allowed us to confirm the flatness of space [15]. (Recent claims to the contrary [16], remain a possibility, albeit a very improbable one.) They have also allowed us to learn when the first stars were born (roughly at 200 million years).

Understanding the nature of time remains one of the great challenges of physics. A classical theory of gravity (and thus the big bang model) predicts the existence of an “initial singularity,” the instant in time when the energy density reaches an infinite value and space collapses to a point. At the heart of the problem is a proper formulation of a quantum theory of gravity, explaining its behavior at very small distances and high energies. Although there are models describing the origin of the universe (at least our local patch) by a quantum tunneling event [17, 18], the transition from a quantum to a classical universe one described by the big bang model remains obscure. We need guidance from particle physics to pick the proper theory to work with. String theory [19] and/or loop gravity [20] have made much progress, but we still don’t have a compelling connection between their realm and that of 4-dimensional spacetime particle physics.

IV. MATTER

It must be clear to the reader that within modern cosmology, treating space, time, and matter as three separate topics is highly artificial. The three are deeply intertwined. A point in case is the questions of the “end of time” [2]. Up to 1998, the standard big bang model had a very simple prediction: if we know the total energy density of the universe (ρ_{tot}), we can tell what will happen to it. The cosmic fate is controlled by the critical density, $\rho_{\text{crit}} = 3H_0^2/8\pi G \simeq 10^{-29}$ g/cm³, where G is Newton’s gravitational constant. It is convenient to define the ratio $\Omega_i \equiv \rho_i/\rho_{\text{crit}}$ for a given contribution to ρ_{tot} . Of course, $\rho_{\text{tot}} = \sum_i \rho_i$, and $\Omega_{\text{tot}} = \rho_{\text{tot}}/\rho_{\text{crit}}$. If $\Omega_{\text{tot}} > 1$, the universe will recollapse in the distant future. Otherwise, it will continue its expansion indefinitely. The discovery in 1998 that the universe is presently accelerating blurred the clarity of this prediction [21]. The culprit of this acceleration is called dark energy, a ghostly contribution to the total energy density (and pressure, which makes ‘dark energy’ a somewhat imprecise name) spread out homogeneously or nearly so across the universe. Its net effect is to push the cosmic geometry apart, somewhat like an anti-gravitational force. Measurements of distant supernovae and of the CMB give $\Omega_{\text{DE}} \simeq 0.73 \pm 0.04$. So, not only there is an unknown energy component in the universe, but it is also the

dominant one: CMB and other measurements place $\Omega_{\text{tot}} = 1.02 \pm 0.02$, meaning that everything else must amount to no more than 27% or so of cosmic stuff. Most probably this implies that the universe is marginally flat and hence will expand forever. But what if the universe were supercritical ($\Omega_{\text{tot}} > 1$)? Without dark energy (pre 1998), we would say it would recollapse in a finite time. But with dark energy things are more subtle [2, 22].

Dark energy is extremely difficult to pinpoint; its effects on the CMB are mostly relegated to very large fluctuations. The two main contenders are the infamous cosmological constant, created by Einstein to balance out his collapsing static spherical model, and a hypothetical scalar field called quintessence [23]. The main difference between a cosmological constant and a scalar field is in their pressures and clustering properties. Scalar fields may have pressures of smaller absolute magnitude and respond to variations in the gravitational field: *i.e.*, quintessence may cluster, even if very subtly. The problem is that the models for quintessence are somewhat contrived, at least from a particle physics viewpoint. If quintessence exists, it will almost certainly not be a fundamental field, but a phenomenological order parameter or condensate of some sort. The cosmological constant is not in much better shape. Quantum physics predicts that all fields have a sort of fundamental inescapable jitter. Since all that moves carry energy, this quantum jitter has an associated energy, called zero-point energy [24, 25]. This energy is most certainly related to the cosmological constant. Quintessence has nothing to say about this. The problem is, if one would naively compute the zero-point energy in the universe, the result would be a cosmological constant some 120 orders of magnitude too large. In other words, we don't understand the cosmological constant. Until we have a better grasp of it, dark energy will remain mysterious.

What then is the cosmic recipe, *circa* January 2004? Taking $\Omega_{\text{tot}} = 1$, the total normal (baryonic) matter and dark matter components add up to 27%, or $\Omega_{\text{M}} + \Omega_{\text{DM}} = 0.27$. Nucleosynthesis constrains $\Omega_{\text{M}} \simeq 0.04$, leaving $\Omega_{\text{DM}} \simeq 0.23$. That measurements of the distribution of dark matter in galaxies and clusters of galaxies, as well as CMB measurements, concur very nearly with this estimate speaks to the robustness of modern observational and theoretical cosmology. It turns out that the stuff we and stars are made of is by far the universe's subdominant energy component. Even this familiar component is only partially accessible; some of ordinary matter is also "dark" in the sense that it does not produce visible radiation. (But it produces other kinds of radiation, such as infrared, as we have seen in the hunt for extrasolar planets.) However, the bets are still off for what is the dark matter component. Unless we are missing something very basic about gravity at large distances, dark matter is not of the ordinary kind. It may not be of a single kind either: maybe several exotic particles and more complex objects contribute to Ω_{DM} . A tremendous amount of effort is being dedicated to disclose some of its nature, be it by direct detection (cryogenic detectors that would "count" the dark matter particles as they impact its collecting area or resonate in special cavities) or by production in the laboratory (if dark matter is related to supersymmetry, it may possibly be produced in particle accelerators very soon [26].) Whatever dark matter is, the stakes are high: we are talking of an unknown kind of matter, over six times more abundant in the universe than ordinary matter. Both dark energy and dark matter promise new physics ahead.

V. CONCLUSIONS

I hope this brief overview has given the reader at least a general flavor of the excitement permeating present cosmological and astrophysical research. We have learned a tremendous amount about the physical universe, its material composition, its shape, and its age. Yet, science teaches us that there will always be more to learn. In fact, the old aphorism, "the more we know the more we don't know" seems to apply very well here. As new tools and ideas open new vistas to the physical universe, we stand in awe of nature's creativity and of our ability to understand so much of it. To those that cynically comment on the state of "mystery" in cosmology, "too much dark stuff around," I say that this is precisely how science progresses: by teaching us to accept ignorance as the main precondition for learning. Only then we stand a chance of rationally answering some of the many questions we have, and the many more that will surely come. What we have learned so far speaks for itself.

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